Gravitational Microlensing: Black Holes, Planets; OGLE, VLTI, HST and Space Probes

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ABSTRACT

OGLE and other projects are likely to discover first stellar mass black holes and the first planets through gravitational lensing in the next year or two. It is important to have follow-up projects ready, using diverse observing methods. The best for black hole detection would be a measurement of image splitting with VLTI, or any other optical interferometer. Alternative approach is to measure non-linear motion of the light centroid with the HST, or even with a ground based telescope. Every year OGLE detects several very long duration microlensing events brighter than $I=16$ mag and $K=14$ mag. The two images may be separated by up to 10 mas.

Ground based detection of strong caustic crossing planetary events will provide mass ratios and proper motions for the detected systems. For most events photometric parallax needed for mass determination will require a space instrument at least as far as the L2 point, to provide long enough baseline.

Key words:*Astrometry- Black Holes - Dark matter - Gravitational lensing - Planets*

1. Introduction

The main purpose of this paper is to bring to reader's attention the current status of microlensing searches. It is likely that within a year or two these searches will lead to firm discoveries of stellar mass black holes and planets. The paper is centered on current developments at the Optical Gravitational Lensing Experiment (OGLE, Udalski et al. 1997, 2002). It is motivated by the fact that OGLE team is small and hence not in a position to do the diverse follow-up observations, which are needed to make conclusive case for black hole lenses, or to measure planetary masses. This is one of the reasons the OGLE data are made public domain with no strings attached, so other teams or individuals may use them as the basis for their own follow-up projects.

The search for gravitational microlensing, and follow-up observations, are a well developed 'industry', with dozens of events reported every year in real time by the MOA collaboration (Bond et al. 2001):

http://www.roe.ac.uk/%7Eiab/alert/alert.html

and hundreds reported by the OGLE collaboration (Udalski et al. 1997, 2002):

http://www.astrouw.edu.pl/~ ogle/ogle3/ews/ews.html

A major increase in the discovery rate is to be expected when the upgrade of MOA capability is completed, with the first light from the new 1.8 meter telescope expected in 2004 or 2005:

http://www3.vuw.ac.nz/scps/moa/

While there is a very large diversity of research topics related to microlensing, as well as very many other results of the surveys (cf. Paczyński 1996a, Gould 2001, and references therein), this paper is focused on just two extreme cases: the search for black holes and the search for planets, i.e. very large and very small mass lenses. A definite detection of stellar mass black holes and planets is an interesting goal, almost certainly achievable within a year or two. Only microlensing is capable of detecting Earth mass planets and isolated black holes with the technology which already exists. This paper outlines OGLE contribution to the task. However, to be successful it requires diverse follow-up observations to be carried out by astronomers not necessarily associated with OGLE.

2. Black Holes

The discovery of long duration microlensing events prompted suggestions that some of the lenses may be due to stellar mass black holes (Bennett et al. 2002a,b; Mao et al. 2002; Smith 2003). The argument is simple: the time scale of a microlensing event, i.e. the time t_E it takes a lens to move with respect to the source by the Einstein radius φ_E is given as (cf. Paczyński 1996a, and references therein)

$$t_E = \frac{\varphi_E}{\dot{\varphi}} = 1.01 \ yr \ \left(\frac{M}{M_\odot} \right)^{1/2} \left(\frac{8 \ kpc}{D} \right)^{1/2} \left(\frac{1 \ mas \ yr^{-1}}{\dot{\varphi}} \right), \tag{1}$$

where $\dot{\varphi}$ is a relative proper motion of a lens with respect to the source, M is the lens mass, and D is the effective distance defined as

$$D = \frac{D_s D_d}{D_s - D_d}, \tag{2}$$

where D_s is the distance to the source, and D_d is the distance to the lensing object (deflector). The angular Einstein radius is given as

$$\varphi_E = 1.01 \ \mathrm{mas} \ \left(\frac{M}{M_\odot} \right)^{1/2} \left(\frac{8 \ kpc}{D} \right)^{1/2} . \tag{3}$$

In most cases the distance to the source is either known or may be estimated, but the distance to the lens, its mass, and its proper motion with respect to the source, are not known. The time scale of a microlensing event, t_E, is directly measured, and the longer it is the larger the lens mass, other things being equal. Unfortunately, other things (D_d and $\dot{\varphi}$) are not equal and may very a lot from one event to another. Therefore, a long duration is only an indication of a large mass, but only in a statistical sense.

For long events the effect of Earth's motion around the sun makes the relative motion in the observer – lens – source system not linear (Refsdal 1966, Gould

1992), and leads to the so called photometric parallax effect, which is always measured for long events. The most spectacular case known so far is that of OGLE-1999-BUL-19 (Smith et al. 2002), in which several maxima were observed as a consequence of the Earth's orbital motion. The amplitude of the parallax effect provides additional information, and partly removes the degeneracy in the eq. (1). The smaller the relative proper motion $\dot{\varphi}$, the stronger the effect. In the case of OGLE-1999-BUL-19 it was clear that the relative proper motion $\dot{\varphi}$ was very small, and that small velocity was responsible for the long time scale, $t_E = 1.02$ years, while the lens mass was sub-solar.

More interesting was OGLE-1999-BUL-32 = MACHO-99-BLG-22 (Mao et al. 2002, Bennett et al. 2002b), the longest event so far, with t_E=1.75 years, and clearly measured, but small parallax effect, indicative of a large relative proper motion, and hence a large lens mass. This is currently the best candidate for gravitational microlensing due to stellar mass black hole, but the mass estimates requires statistical analysis, which is not very reliable. In fact the probability estimate that the lens is a black hole changed from 20% to 76% between v1 and v4 edition of astro-ph/0203257 (Agol et al. 2002). It is not possible to make a credible probability estimate as the stellar mass function, all the way from brown dwarfs to intermediate mass black holes, is not known.

The second strong black hole candidate is OGLE-SC5_2859 (Woźniak et al. 2001). With t_E=1.5 years this is the second longest event known. The parallax effect is clearly detected, but its amplitude is small. However, there may be other complications (Smith 2003),

Unfortunately, in all cases so far the third quantity which is in principle observable: φ_E, remains unknown. In fact there is not a single microlensing event for which Einstein radius was directly measured. The reason is simple: the expected value of φ_E is of the order of a milli arc second (Eq. 2), well below the resolution of existing optical instruments. There is only one case, EROS BLG-2000-5, a binary lens, for which it was possible to infer $\varphi_E = 1.4$ mas as the proper motion was measured with caustic crossing, and photometric parallax effect was also detected (An et al. 2002). The total mass of the lens, and the mass ratio, were found to be 0.61 $M_\odot$, and M_2/M_1=0.748, respectively.

2.1 Resolving Microlensing - VLTI

A direct method to measure φ_E was proposed by Delplancke et al. (2001): to resolve the double image generated by microlensing with an optical interferometer, specifically VLTI. The first papers with the first results from VLTI are already published (Segransan et al. 2003), or posted (Kervella et al. 2003), and perhaps VLTI will soon be used to measure microlensed stars.

For an event well covered photometrically the dimensionless angular separation between the source and the lens is known as a function of time:

$$u = \frac{\varphi}{\varphi_E} = \left[u_{min}^2 + \left(\frac{t - t_{max}}{t_E} \right)^2 \right]^{1/2} , \qquad (4)$$

where φ is the angular separation between the lens and the source. The combined brightness of the two images is larger than the source by the so called magnification factor A:

$$A = \frac{u^2+2}{u\sqrt{u^2+4}}. \tag{5}$$

The magnification is the largest when the separation is the smallest, i.e. when $u = u_{min}$, which happens at the time $t = t_{max}$. Photometric model of a well observed microlensing event provides accurate values of u_{min}, t_{max}, and t_E.

The two images have opposite parity: one positive, with magnification A_+, always located outside of Einstein circle, another negative, with magnification A_-, always located within Einstein circle. We have

$$A_+ + A_- = A, \qquad A_+ - A_- = 1. \tag{6}$$

The two images are separated by an angle $\Delta\varphi_{+,-}$ given as

$$\frac{\Delta\varphi_{+,-}}{\varphi_E} = \sqrt{u^2+4}. \tag{7}$$

A single measurement of the angular separation $\Delta\varphi_{+,-}$ between the two micro-images provides a direct determination of angular Einstein radius, as $u(t)$ is provided by the photometric model of the event. While such a measurement is very robust and elegant, the VLTI (or any other optical interferometer) has to be able to observe stars as faint as those which are microlensed. Several microlensed stars are bright, with $I \sim 16$ mag, and $K \sim 14$ mag. At peak magnification some reach $I \approx 14$ mag, i.e. $K \approx 12$ mag. Bright, long duration OGLE events are described in the Section: *Long Current Events*.

2.2 Astrometric Shift - HST

An alternative astrometric approach is not to resolve the double image, but to measure the motion of the light centroid (Hog et al. 1995, Miyamoto and Yoshi 1995, Walker 1995, Boden et al. 1998, Paczyński 1998). In all these papers it was suggested that a space probe, GAIA or SIM:

http://astro.estec.esa.nl/GAIA/
http://sim.jpl.nasa.gov/whatis/

will be able to do micro arc second precision astrometry, and therefore will be able to determine angular Einstein radii for virtually any microlensing event.

The light centroid shifts with respect to the source position by

$$\delta\varphi = \frac{u}{u^2+2}\ \varphi_E, \tag{8}$$

The displacement reaches maximum value $\delta\varphi_{max}$

$$\delta\varphi_{max} = 2^{-3/2}\ \varphi_E \approx 0.354\ \varphi_E \quad \text{for} \quad u_{max} = 2^{1/2} \approx 1.414. \tag{9}$$

This angular separation corresponds to a magnification $A = 1.155$, i.e. 0.156 mag above the baseline. The full range of displacements, from the moment

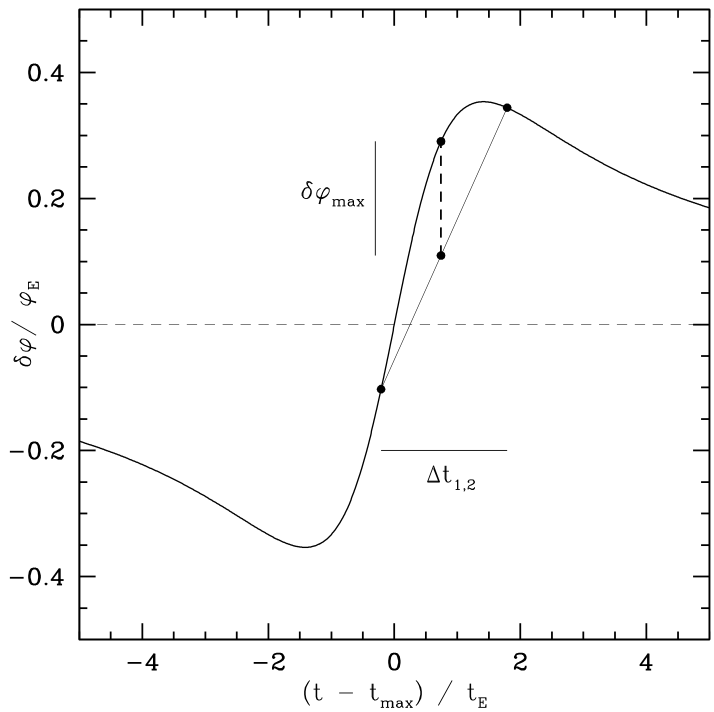

Figure 1: The motion of the light centroid is shown as a function of time for a simple case, when the impact parameter for microlensing is exactly zero. For a given value of observing time interval, $\Delta t_{1,2}$, there is an optimum choice of the beginning and the end of observing, t_1 and t_2, respectively, which maximizes the nonlinearity of proper motion, $\delta\varphi_{max}$. An example shown corresponds to $\Delta t_{1,2} = 2t_E$.

when $A = 1.155$ on the rising branch, to the moment when $A = 1.155$ on the descending branch, is $t_E \times 2 \times 2^{1/2} \approx 2.8 t_E$. This is inconvenient, as we are targeting long duration events, with $t_E > 1$ year.

While SIM and GAIA will be able to do a superb job in measuring the shifts in the light centroids of almost all selected microlensing events, they are scheduled for launch in 2009 and in $2010 - 2012$, respectively. This is a long time to wait. In this paper I am most interested in a possibility of identifying black hole lenses, and in measuring their masses in the next year or two. The best candidates for such studies are the longest microlensing events, which are likely to have the largest Einstein radii, probably in the range of several milli arc seconds. Small angle astrometry can be done with the HST with a precision of a fraction of a milliarcseconds (cf. Fritz et al. 2002, and references therein). Perhaps modern large telescope can also achieve such precision. The advantage of this approach is that the brightness of the lensed star is not a problem, but many images covering a substantial time interval have to be obtained. As we are focusing on long duration events, the time interval may be several years.

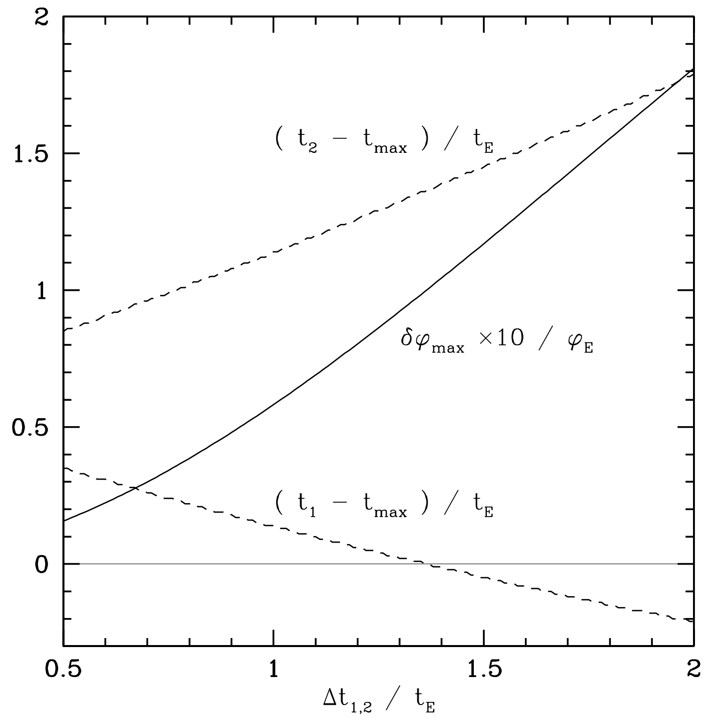

Figure 2: For a given time interval of observations, $\Delta t_{1,2} = t_2 - t_1$, the non-linearity of centroid proper motion δ_φ depends on the choice of t_1. The figure shows the values of t_1 and t_2 which maximize δ_φ, as a function of $\Delta t_{1,2}$).

The following is an illustration of what may be expected. For simplicity I assume that the impact parameter of the lensing event is very small, i.e. $u_{min} \ll 1$, and hence the maximum magnification will be very large, $A_{max} \gg 1$ (cf. eqs. 4, 5). This implies that the source moves along a line in the sky which passes almost exactly behind the lens, the relative proper motion is one-dimensional, and so is the shift of the light centroid. This makes the presentation of motion very simple. The time dependence of centroid displacement with respect to the source is shown with solid line in Fig. 1. The maximum range is $0.707\varphi_E$, but it takes time interval of $2.83t_E$, as given with the eqs. (9). Unfortunately, we do not know the asymptotic motion of the source, unperturbed by lensing. To learn this we would have to monitor it for a very long time indeed, as the solid line in Fig. 1 approaches the unperturbed source position very slowly, as $1/t$. What can be measured within a reasonable time interval is the non-linear motion of the light centroid. In most cases of interest the astrometric parallax effect due to Earth orbital motion is negligible (Figs. 1 and 2 in Paczyński 1998), so it is sufficient to calculate the departure from linear motion based on Fig. 1.

Let us assume that astrometric measurements are done over time interval $\Delta t_{1,2}$, beginning at some time t_1, and continued till t_2. For a given value of $\Delta t_{1,2}$ we want to select the beginning of astrometric observations t_1, to maximize the

deviation of centroid position from a linear proper motion. For example, the two dots on the solid curve in Fig. 1, connected with a straight solid line represent an example for $\Delta t_{1,2} = 2t_E$. The vertical dashed line represents the maximum value of departure from linear motion, in this case it is $0.18\varphi_E$.

More general results are shown in Fig. 2, where the beginning and the end of observations, t_1 and t_2 are shown with dashed lines as a function of $\Delta t_{1,2}$, all in units of Einstein time scale t_E. The maximum displacement with respect to linear proper motion in the considered time interval is shown with thick solid line, with the value of $\delta\varphi_{max}$ multiplied by a factor 10. It is interesting that $\delta\varphi_{max}$ is approximately a linear function of $\Delta t_{1,2}$.

Fig. 2 presents a practical problem with astrometry of centroid shift of long microlensing events: in order to detect a substantial non-linearity of centroid proper motion it is necessary to monitor it for a long time. For example, if $t_E = 1.5$ years, and $\varphi_E = 5$ mas, then monitoring the motion over 3 year time interval provides us with the maximum displacement $\delta\varphi_{max} = 0.18 \times \varphi_E = 0.9$ mas. It is convenient that astrometry has to begin not much earlier than the peak magnification. By that time all photometric parameters of the microlensing event are fairly well known,

2.3 Long Current Events

It is fortunate that to achieve the largest non-linear shift in the light centroid there is no need to begin astrometry while the microlensing event is not fully developed. The OGLE EWS alert is usually issued when the apparent magnitude of a candidate event is $0.2 - 0.3$ mag above the baseline. At this early stage it is not always clear how long the event is going to be, what will be its peak magnification, and even will it be a microlensing event at all. As explained in previous section it is reasonable to begin accurate astrometry some time prior to the peak magnification.

In the past the longest microlensing events: OGLE-1999-BUL-32, OGLE-SC5_2859, and OGLE-1999-BUL-19, were all recognized as very long well past their peak, analyzing archive data. There were two main reason for this time lag: improved photometric accuracy had to be developed, using new image subtraction software (DIA - Difference Image Analysis: Alard and Lupton 1998, Alard 2000, Woźniak 2002), and it had to be recognize that events with a time scale well over a year existed. The DIA is now used in real time data analysis, and it is known that very long events exist, so the task of early recognition of the very long events is now easy.

The following is the current status of OGLE EWS results. The unfolding OGLE-2003-BLG-192 has barely begun its rise, with the time scale estimate $t_E \approx 235$ days. The lensed star is bright: $\mathrm{I} = 16$ mag, but the expected peak magnification is low. At this time it cannot be guaranteed that this is a microlensing event.

There are several other long events just beginning their rise, with $I \sim 16$ mag, or brighter: OGLE-2003-BLG-047 with $t_E = 156$ days, OGLE-2003-BLG-188 with $t = 121$ days. OGLE-2002-BLG-360, with $t_E = 270$ days, is close to

its peak at $I = 14.2$. Two bright and long events are almost over: OGLE-2002-BLG-061 with $t_E = 305$ days, and OGLE-2002-BLG-334 with $t_E = 160$ days. Many more long events are faint at their baseline, heavily blended and therefore not very useful. However, several events every year are long and reasonably bright, with $I \leq 16$ mag. This may be time to propose follow-up astrometric observations for some of these events. Most lensed stars are in the Galactic Bulge and they are red, with $(I - K) \geq 2$ mag, i.e. the bright events have $K < 14$ mag.

3. Planets

Another high profile discovery which is likely to result from microlensing is the first firm detection of a planetary signal, as proposed by Mao and Paczyński (1991). There is a rich literature on the subject, devoted to various aspects of planetary lensing, and how to recognize it. As planetary events are even less probable than stellar, a lot of theoretical effort was directed to increase the probability, at the cost of seeking low amplitude signals. This may be a good approach, but not at the beginning of a search. Right now we need credible events with no ambiguity about their interpretation. In other words, one needs an 'overkill' evidence to be persuasive the first time, and perhaps even the first several times. Such clear planetary signal will be present in caustic crossing events, like those shown in Fig. 10 of Paczyński (1996a). Even Earth mass planet can generate a complicated disturbance in a stellar microlensing light curve, with an amplitude of 20% or more. Such events are far less frequent than 5% or 2% amplitude planetary disturbances, but they offer unambiguous evidence of a planet, and an unambiguous mass ratio. Also, as any caustic crossing event, they will provide the information about the relative proper motion $\dot{\varphi}$ (Gould 1994, Graff and Gould 2002).

While any strong planetary event is likely to provide the mass ratio and a relative proper motion, it is necessary to measure also photometric parallax effect to determine the mass. This may be possible in some cases, when the stellar event time scale t_E is long, but in general this can be done only with spacecraft observations (Gould 1995, Gould et al. 2003), as they provide a baseline for the photometric parallax determination. Following the analysis of a possible planetary signal from OGLE-2002-BLG-055 (Jaroszyński and Paczyński 2002) the EWS alert system on OGLE has been upgraded to EEWS (Early Early Warning System), capable of recognizing and verifying in real time possible planetary disturbances in stellar microlensing events (A. Udalski, 2003, private communication). No structure is expected on a time scale shorter than ~ 1 hour, as it takes so long for a source star to move by its own radius. Therefore, instant follow-up observations at ~ 30 minute intervals are planned by the OGLE when a plausible planetary disturbance will be recognized. The new system should be much more sensitive to planet detection that the past attempts, which generated only upper limits (e.g. Gaudi et al. 2002).

The most natural follow-up observations are photometric measurements to

be done from other location, to provide full time coverage. There are several other active microlensing projects: MOA (Mond et al. 2001), PLANET (Albrow et al. 2002), MPS (Rhie et al. 1999), GMAN (Becker et al. 1997, Bennett et al. 2002a), MicroFUN (A. Gould, 2003, private communication)

http://www.astronomy.ohio-state.edu/˜ microfun

This coverage should be adequate to obtain the mass ratio, a clear indicator of a planetary presence. Spacecraft observations are needed to determine the masses, as well as the linear planet - star separations (in Astronomical Units).

4. Conclusions

It is very likely that stellar mass black holes and planets will be discovered in the next year or two. OGLE is generating several bright and long duration microlensing events every year (cf. Section 2.3), and these are promising candidates for stellar mass black holes. All these events have not only their times scales t_E measured, but also the photometric parallax effect. To make a definite case for black holes it is necessary to measure their angular Einstein radii, φ_E. This could be done best with an optical interferometer, possibly with VLTI (Delplancke et al. 2001). An alternative approach is to carry out accurate astrometric monitoring and to detect a non-linear motion of the light centroid with the HST, or perhaps even with new large ground based telescopes. A lens with $\sim 10\ M_\odot$ is likely to have $\varphi_E \sim 3$ mas. If intermediate mass black holes exist (Madau and Rees 2001, Chisholm et al. 2002, Wu et al. 2002, and references therein) the corresponding image splittings could be much larger, with $\varphi_E \sim 10$ mas, and perhaps even more. Such events would make image centroid motion easily detectable not only with the HST, but also with ground based telescopes.

Once several firm planetary detections are made we shall be in a much better position to plan future upgrades of planetary microlensing searches. It is likely that the detection threshold could be lowered to improve the statistics without compromising credibility. But a major improvement will require a major increase in the photometric data rate, to monitor more stars more frequently and with a higher photometric accuracy. Note: vast majority of microlensing events are heavily blended and are relatively faint. It will take a lot of photons to reliably search them for small planetary disturbances.

While OGLE and other ground based telescopes will determine the mass ratios for star - planet systems, and the source - lens proper motion in caustic crossing events, only some of them will have large enough t_E to allow photometric parallax to be measured from the ground (cf. Jaroszyński and Paczyński 2002), and to determine the masses as well. In most cases it will take space instrument to provide a large baseline to measure photometric parallax effect, and hence the masses for most of them (Gould 1995, Gould et al. 2003).

This paper is posted on astro-ph only. Its purpose is to outline prospects for various space and ground based projects which are needed to provide definite evidence for stellar mass black holes and planets, using OGLE as a search tool.

Acknowledgements. This research was supported by the NASA grant NAG5-12212 and the NSF grant AST-0204908.

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